Circumarctic Map of Permafrost and Ground Ice Conditions

First Published: December 1993 in *Permafrost: Sixth International Conference*, Beijing, Proceedings. Wushan, Guangzhou, China, South China University Press, volume 2, pp. 1132-1136.

Revised: 19 December 1997

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ABSTRACT

The International Permafrost Association (IPA) undertook to compile and publish this circum-arctic permafrost map, in response to a recognized need for a single, unified international map to depict the distribution and properties of permafrost in the Northern Hemisphere at a scale that would be useful to both permafrost and non-permafrost specialists concerned with global climatic change, resource development in polar regions, and protection of the environment. The map shows the estimated permafrost extent by percent area (90-100%, 50-90%, 10-50%, <10%, and no permafrost present); an estimate of relative abundance of ice in the upper 20 meters as percent volume (>20%, 10-20%, <10%, and 0% or nil); relative abundance of ice wedges, massive ice bodies and pingos; ranges of permafrost temperatures (C) and thicknesses (meters), and the location of subsea and relict permafrost, and cryopegs or unfrozen layers. The map is accompanied by four cross sections of the permafrost region, illustrating the thickness and nature of permafrost.

1 INTRODUCTION

In 1990, the International Permafrost Association (IPA) recognized the need for a single, unified international map to depict the distribution and properties of permafrost in the Northern Hemisphere at a scale that would be useful to both permafrost and non- permafrost specialists concerned with global climatic change, resource development and protection of the environment, such as the Intergovernmental Panel on Climate Change, and the United Nations Environment Program. To address this concern, the IPA, at its Council meeting of June 1990 in Quebec City, Canada, approved the compilation and publication of a circum-arctic permafrost map. It was agreed to produce the map for the Sixth International Conference on Permafrost, and also that other national and international scientific and engineering organizations would be notified of the project and their cooperation and participation invited. The project, which was coordinated by the IPA Editorial Committee, consisted of five major steps: (1) legend development, (2) initial compilation for North America and Russia by the authors, (3) additional input by national experts for China, other Asian countries and the Nordic and European countries, (4) review and revision, and (5) final cartographic preparation and printing. The United States Geological Survey agreed to support the development of the map by providing cartographic, printing and publishing services, as part of the Circum-Pacific Geological Map project.

The map presents the most significant permafrost or geocryological conditions, namely areal distribution, thickness, temperature, and ground ice characteristics. Deep-lying (relict) and subsea permafrost are also represented.

2 HISTORY AND CLASSES OF PERMAFROST MAPS

This brief review of permafrost mapping is based on the paper by Heginbottom (1984). According to Nikiforoff (1928) and Baranov (1959), the earliest known map depicting permafrost was prepared by G. Vil'd of Siberia; it was published in 1882 and shows the southern boundary of the "ever-frozen region". The earliest map known for North America is credited to Andre in 1913 by Baranov (1959), but unfortunately the reference is not cited and the original work has not been identified. Since these early efforts, over 150 different maps of permafrost and related phenomena have been compiled and published. Heginbottom (1984) grouped these maps into four categories:

1. Miniature maps of the world, the northern polar regions, or the northern hemisphere continents showing the distribution of permafrost as known at the time of their compilat ion. These maps range in scale from about 1:30,000,000 to about 1:50,000,000. Examples include maps by Black (1954) and Péwé (1983).
2. National maps showing the distribution of permafrost for the politically defined areas. Scale and level of detail vary widely according to the size of the area covered. These maps can be grouped according to size as single page maps, typically at scales of between 1:50,000,000 and 1:10,000,000, and atlas or wall maps on larger sheets, at scales of between 1:10,000,000 and 1:2,500,000. Examples of the first subclass are Rapp and Annersten's map (1969) of discontinuous permafrost in Sweden, Weidick's map (1968) of the extent of permafrost in Greenland and Ershov's compilations (1988,1989) for the former Soviet Union. Examples of maps in the latter subclass include Brown's map (1978) of Canada, the map of China by Shi and Mi (1988), Ferrians' map (1965) of Alaska, the maps of the USSR and North America by Popov et al. (1985, 1990), a map of Mongolia (Sodnom and Yanshin, 1990), and a new map of permafrost and ground ice in Canada (Heginbottom and Dubreuil, 1993,).
3. Regional and local maps of permafrost or ground ice conditions or related features, which are available for many areas and at a variety of scales. Examples of these maps include Melnikov's map (1966) of Yakutia, Péwé's map (1982) of the Fairbanks area of Alaska, maps of West Siberia by Baulin (1982), and of the Qinghai-Xizang Highway by Tong et al. (1982), and Heginbottom and Radburn's map (1992) of north-western Canada.
4. Maps of various areas showing the former extent of permafrost or the distribution of permafrost conditions, such as Kaiser's map of western and central Europe, published in Washburn (1990).

Maps can also be grouped by their contents or legend, the most common showing the extent and distribution of `climatic permafrost', as defined by climatic conditions and usually divided into the continuous and discontinuous zones (e.g. Brown, 1973). Some maps in this group show areas of alpine or mountain permafrost (e.g. Brown, 1967 and Gorbunov, 1978) and subsea permafrost (Mackay, 1972 and Péwé, 1983). A second set of maps show specific attributes such as thickness and temperature of permafrost (Judge, 1973; Ershov, 1989) and the distribution of geomorphic features indicative of the occurrence of ground ice, of frozen ground, or of the former extent of frozen ground (Popov et al., 1966), including pingos (Hughes, 1969), ice-wedge polygons or ice wedges (Shumskiy and Vtyurin, 1966), and ice-wedge casts (Williams, 1969). A third group of maps relates permafrost conditions to environmental conditions including temperature (Crawford and Johnston, 1971), extent of glaciation (Hughes, 1973), and geology, hydrology or vegetation (e.g. Ferrians, 1965; Fotiev, 1978; Bliss, 1979). Complex maps contain environmental, permafrost and ground ice information. Such maps have more often been prepared in the former Soviet Union (e.g. Baranov, 1956, 1965, 1982; Kudryavtsev et al., 1978; Melnikov, 1966; Fotiev et al., 1978; Vtyurin, 1978; and Ershov, 1989).

2.1 Principles and Methods of Compilation

A major problem in the compilation of maps of complex natural phenomena over very large areas is the variation in the level and accuracy of the available data and information. The principles and methods used in compiling this circum-arctic map recognize and accommodate this difficulty. The variations encountered relate both to disparities in the level of field observations, and to variations in environmental and geological factors which control the distribution and attributes of the permafrost and ground ice.

The mapping strategy originally proposed was to delineate landscape units, employing a common physiographic classification of the Northern Hemisphere, and to assign legend attributes in each identifiable unit. This approach was not feasible, however, since no physiographic map of the northern regions of the earth, at the desired scale and level of detail, was readily available and it was beyond the scope of this project to prepare one. It was decided therefore to use existing physiographic or landscape maps in each of the three major national permafrost regions (Russia, Alaska, and Canada). In preparing this map no attempt was made to conduct new field studies and every attempt has been made to use all readily available published and unpublished information.

Map units in Alaska are based on the 1965 map "Physiographic Divisions of Alaska" (Wahrhaftig 1965) and contain information being used to revise the 1:2,500,000 map of Alaska (Ferrians 1965). The Canadian contribution utilizes the 1967 map "Physiographic Regions of Canada" (Bostock, 1970) as a base map and contains much of the information presented on the new permafrost and ground ice map prepared for the 5th edition of the National Atlas of Canada, (Heginbottom and Dubreuil, 1993, 1995). Russian map units are derived from the geosystems or landscape approach described by Melnikov (1988), in which natural geosystems are delineated according to common relief, vegetation, soil and soil-forming materials and climate. Units for China and Mongolia are based on recompilations of the maps by Shi and Mi (1988) and from Sodnom and Yanshin (1990), respectively. Existing information for the Nordic countries, Greenland, and other mountainous regions of Europe and Asia were modified and compiled from numerous published and unpublished sources with the assistance of regional specialists, as listed in Table 1.

A preliminary legend was agreed to by the principal authors in Anchorage, Alaska, in September 1991 and revised by the same authors in Ottawa, Canada, in April 1992. The map scale of 1:10,000,000 was selected so that all regions of permafrost occurrence in the Northern Hemisphere could appear on a single map sheet. The map extends southward to 20°N latitude and includes mountain or high-altitude permafrost conditions in Tibet, Scandinavia and central Europe, the Cordillera of North America and mountainous regions of southwestern, central and eastern Asia. A Lambert Polar Azimuthal Equal Area map projection, centered on the north pole, was selected for the map, so that regions of similar latitude would have comparable areas. This feature of the projection was considered important for global change considerations related to potential changes in areal extent of permafrost and ground ice distribution and volumes. A base map was computer generated by the U.S. Geological Survey, Reston, Virginia, USA, using existing World Data Bank II data bases for coastlines, drainage, the latitude and longitude grid, and international boundaries. Glaciers and ice caps for North America, including Greenland, are based on digitized files from Canadian sources. The Canadian contribution was prepared from computerized data bases (Heginbottom and Dubreuil, 1993).

3 MAP DESIGN AND THEMATIC CONTENT

The map is a comprehensive summary of permafrost and ground ice conditions in the northern circum-polar region. The basic map units are described in terms of the extent of permafrost, the quantity of ground ice, and the relative abundance of larger bodies of ground ice: pingos, ice wedges and bodies of massive ice. Note that no distinction is made between massive ice of intrasedimental origin (Mackay and Dallimore, 1992) and massive ice resulting from the burial of ice formed at the ground surface, such as buried glacier, river or icing ice. Information on permafrost thickness and ground temperatures is given for selected localities across the region.

3.1 Permafrost Extent

The general distribution of permafrost and ground ice is divided first into two broad classes, based on regional elevation, physiography and surface geology. Group 1 comprises areas of lowlands, highlands and intra- and inter-montane depressions characterized by thick overburden, wherein ground ice is expected to be generally fairly extensive. The second group covers areas of mountains, highlands, and plateaus characterized by thin overburden and exposed bedrock, where generally lesser amounts of ground ice are expected to occur. For the purposes of this map compilation, thick overburden is defined as being greater than 5 to 10m.

The estimated extent of permafrost in each map unit is presented in four classes, based on the percentage of the ground that is underlain by permafrost (continuous, 90-100%; discontinuous, 50-90%; sporadic, 10-50%; and isolated patches of permafrost, 0-10%). Areas generally free of permafrost are also indicated. For areas of physiographic class 1, areas of thick overburden, the color scheme uses tones of purple for continuous permafrost, blue for discontinuous permafrost, green for sporadic permafrost and yellow- green for areas where permafrost occurs in isolated patches. For areas of physiographic class 2, areas of thin overburden the color scheme uses tones of tan for continuous permafrost, orange for discontinuous permafrost, brown for sporadic permafrost and red for areas where permafrost occurs in isolated patches.

Areas of deep, relict permafrost in Western Siberia, based on both direct and extrapolated measurements, are shown by blue hatching. For the continental shelves of the Arctic Ocean, the northern limit of the zone of the sea floor wherein subsea permafrost is known or presumed to occur is shown.

For Russia, map units known to contain cryopegs, or layer(s) of unfrozen ground with high salt content, are mapped beneath land areas.

3.2 Ground Ice

The relative abundance of ground ice in each map unit is presented in the form of qualitative estimates of the percentage of ice in the upper 10 to 20m of the ground. These estimates include the volume of segregation ice, injection ice and reticulate ice. Three classes are used for ground ice content (high, >20%; medium, 10-20%; and low, <10%) in areas in physiographic class 1, that is for areas of generally thick overburden. For areas of generally thin overburden (physiographic class 2) only two classes of ground ice are mapped, medium to high (>10%) and low (<10%), due in part to paucity of data.

Gradations in the map colors reflect these distributions, with shades of each color denoting map units with more ground ice and tints indicating map units with less ground ice.

The distribution and relative frequency of known occurrences of large identifiable underground ice bodies are treated separately and shown by symbols. Ice bodies included in this manner comprise the ice cores of perennial frost mounds, especially pingos; ice wedges; and bodies of massive ice, generally tabular in shape. A simple, three step scale of "abundant, sparse, and absent" is used. Surface ice features, including ice caps, glaciers and very large icings, are shown by patterns and symbols.

3.3 Ground Temperature and Permafrost Thickness

Values and ranges of mean annual ground temperatures (Celsius) and permafrost thicknesses (meters) are shown for selected localities across the mapped area. These are based either on measured values or extrapolated observations. The placement of the values in the map unit generally corresponds to the geographic proximity of the measurements.

3.4 Landscape Classification

For Russia, six principle morphogenetic landscape groups are identified: lowland plains, high plains, intra- and inter-montane depressions, plateaus or flat highlands, ridges, and mountains. Overall, for the Russian portion of the map, 19 morphogenetic types of landscapes are identified including, 15 within the first three groups, where accumulative sediments of different origins are well developed. No landscape units are shown within the categories of plateaus and mountains. Erosional or denudational landscape categories have four types.

Major lithological classes present in the upper 10 to 20m of the ground are divided into unlithified and lithified material; the former including peat, clay and silt, sand, and coarse clastic deposits or debris and the latter comprising soluble rocks (e.g.: limestone or dolomite), insoluble rocks and undifferentiated rocks.

3.5 Transects of the Permafrost Region

Four north-south oriented transects of the permafrost region are shown as insets to the map. The transects illustrate the major characteristics of the permafrost body and its ground ice conditions on a hemispheric basis, and in an idealized but representative manner.

- Transect A-A' -- East Siberia: The transect is based on data from boreholes drilled for hydrocarbon exploration, mineral exploration (especially for diamonds) and geological structural research on the Siberian Platform.
- Transect B-B' -- Central Canada and Arctic Islands: In the Arctic Islands, the transect is based on data from numerous boreholes drilled for hydrocarbon exploration. On the northern mainland, it is based on data from the few mineral exploration boreholes which have been drilled, along with a limited number of shallow geotechnical borings.
- Transect C-C' -- Mackenzie Valley: The various Mackenzie Valley pipeline and highway routes, both proposed and constructed, have provided a vast data base for mapping permafrost. These data have been used in compiling this transect. Deeper boreholes, in the Beaufort Sea and Mackenzie Delta areas were also relied on.
- Transect D-D' -- West Siberia: Many boreholes have been drilled for purposes of hydrocarbon exploration throughout West Siberia. This transect is based on data from these borings, supplemented with data from deep geophysical soundings.

3.6 Boundaries, Legend and Sources

Boundaries of permafrost and ground ice map units are shown by a solid line where they are well defined and follow a physiographic unit boundary. Where unit boundaries are gradational or are estimated, a dashed line is used. Other line or symbolic boundaries are shown for morphogenetic groups, types of natural geosystems, and lithologic subgroups. The approximate position of the northern limit of trees (compiled from several National Geographic Society maps) is shown, since this major change in vegetation has important implications for ground temperatures and other ecological parameters.

The explanation of the conventions of the map, the color scheme and the symbols are given in the map legend. A subsidiary legend provides information on the landscape units used for the Russian sector of the map. The principle sources relied on in the compilation of the map are listed.

4 REGIONAL DISTRIBUTION OF PERMAFROST AND GROUND ICE CONDITIONS

For the first time, a permafrost map of the entire circumarctic region has been compiled using a common legend, so that permafrost and ground ice conditions can be accurately evaluated, thus enabling regional and global comparisons to be made.

The map illustrates how the regional distribution of permafrost and the nature and extent of ground ice within the permafrost region of the northern hemisphere vary not only with latitude and altitude, but also in response to differences in climate, topography, bedrock geology and surficial geology. Quaternary history, with alternating episodes of glaciation and deglaciation, and phases of marine and lacustrine submergence and emergence of the land, also had profound effects on the nature and distribution of both permafrost and ground ice.

5 CONCLUSIONS

In preparing this new map, conclusions were drawn about our current knowledge of the distribution of permafrost and ground ice in the Northern Hemisphere and some future information needs. The present map differs from earlier maps of permafrost, first, because it provides information for the whole of the northern circum-polar region and, therefore, for effectively all of the northern hemisphere permafrost region. Secondly, the map shows for the first time, information on the distribution and nature of ground ice in a systematic manner. All this information is presented in relation to landscape or physiographic units, which should facilitate its use in other, global, hemispheric or regional studies of the interaction between the lithosphere, the cryosphere and other environmental parameters.

As has long been known, there is considerable variability in the quantity, distribution and reliability of basic data on permafrost and ground ice. Compilation of the map has made this particularly apparent to the authors. While these variations reflect real differences in geocryological conditions, they are mainly the result of the different amount of research undertaken in different regions, differences in accessibility, natural exposures, resource development activity, and different national philosophies in the conduct of national surveys of natural phenomena.

6 ACKNOWLEDGMENTS

Many individuals and organizations have contributed personnel and other resources to the compilation of this map. Several individuals deserve special recognition for their thoughtful involvement early in the project, including, in particular, Ray Kreig and Yuri Shur, Kreig Associates, Anchorage, Alaska; Vladimir Solomatin, Moscow State University; Stanislav Grechishchev, VSEGINGEO, Moscow; and F.E. Nelson, Rutgers University, USA. The assistance and support of J. Åkerman, W. Haeberli and L. King in obtaining data has been especially helpful. Notwithstanding the valuable input from those named, plus many others, the presentation of the information and mapping approach utilized are the sole responsibility of the authors.

This paper was GSC Contribution number 33793.

Table 1. Regional Contributors to the Project

Region	**Contributors**
Russia, Mongolia	G.F. Gravis, L.A. Konchenko, and L.N. Kritzuk, Committee of Geology; and K.A. Kondrat'eva and S.F. Khrusky, Faculty of Geology, Moscow State University, Russia.
Greenland, North Atlantic Islands, Fenno-Scandia	H.J. Åkerman, University of Lund, Sweden, and Matti Seppälä, University of Helsinki, Finland.
Central Europe	W. Haeberli, Swiss Federal Institute of Technology, Zurich, Switzerland, and L. King, Justus-Liebig University, Giessen, Germany
Southern Europe	F. Dramis, University of Camerino, and C. Smiraglia, University of Milano, Italy.
Romania	A. Kotarba, Polish Academy of Sciences, Krakow, Poland.
Mountains of Central and Southwestern Asia	A.P. Gorbunov, Alma-Alta, Kazakhstan.
China	Guo Dongxin and Qiu Guoqing, Lanzhou Institute of Glaciology and Geocryology, Lanzhou, China.

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